

HyTES: Thermal Imaging Spectrometer Development

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Abstract— The Jet Propulsion Laboratory has developed the Hyperspectral Thermal Emission Spectrometer (HyTES). It is an airborne pushbroom imaging spectrometer based on the Dyson optical configuration. First low altitude test flights are scheduled for later this year. HyTES uses a compact 7.5-12 μ m hyperspectral grating spectrometer in combination with a Quantum Well Infrared Photodetector (QWIP) and grating based spectrometer. The Dyson design allows for a very compact and optically fast system (F/1.6). Cooling requirements are minimized due to the single monolithic prism-like grating design. The configuration has the potential to be the *optimal* science-grade imaging spectroscopy solution for high altitude, lighter-than-air (HAA, LTA) vehicles and unmanned aerial vehicles (UAV) due to its small form factor and relatively low power requirements. The QWIP sensor allows for optimum spatial and spectral uniformity and provides adequate responsivity which allows for near 100mK noise equivalent temperature difference (NEDT) operation across the LWIR passband. The QWIP's repeatability and uniformity will be helpful for data integrity since currently an onboard calibrator is not planned. A calibration will be done before and after eight hour flights to gage any inconsistencies. This has been demonstrated with lab testing. Further test results show adequate NEDT, linearity as well as applicable earth science emissivity target results (Silicates, water) measured in direct sunlight.

TABLE OF CONTENTS

1. INTRODUCTION.....	1
2. OPTICAL DESIGN	2
3. THE QWIP ARRAY.....	3
4. DIFFRACTION GRATING	3
5. SYSTEM SPECIFICATIONS AND RESULTS.....	4
6. REMARKS.....	4
7. ACKNOWLEDGMENTS.....	5
REFERENCES	6
BIOGRAPHY	6

1. INTRODUCTION

The Jet Propulsion Laboratory (JPL) has a long history in developing science-grade imaging spectrometers for remote sensing applications. Examples include the airborne visible infrared imaging spectrometer [1] (AVIRIS) and more recently a compact Offner type imaging spectrometer called the Moon Mineralogical Mapper [2] (M³) which recently completed its mission in orbit around the moon onboard India's Chandrayaan-1.

In late 2006, JPL began the development of a breadboard thermal infrared pushbroom spectrometer named the Quantum Well infrared photodetector Earth Science Testbed (QWEST) as an end-to-end laboratory demonstration of both the thermal Dyson spectrometer as well as the quantum well infrared focal plane technology. The testbed is a precursor to the airborne version under development referred to as the hyperspectral thermal emission spectrometer (HyTES) and funded by the NASA Instrument Incubator Program (IIP). The current effort brings together numerous in-house specialties such as optical design and general spectrometer alignment optimization, precision slit fabrication, high efficiency and low scatter concave diffraction grating design and fabrication, precision mechanical and machining capability and quantum well infrared photo detectors (QWIP) focal plane arrays.

The long wave infrared (LWIR) is typically expressed as the wavelength range between 7 and 14 μ m. Our current demonstration instrument operates from 7.5 to 9.5 μ m and the planned airborne instrument will operate from 7.5 μ m to 12 μ m. Spectral information from this wavelength range is extremely valuable for Earth Science research. The airborne instrument will be used in support of the HypsIRI mission (hypsiri.jpl.nasa.gov) which was recently recommended by the National Research Council in their Decadal Survey. The LWIR component of the HypsIRI mission will address science questions in five main science themes:

Volcanoes

What are the changes in the behavior of active volcanoes? Can we quantify the trace gases (CO₂) released into the atmosphere by volcanoes and estimate its impact on Earth's climate? How can we help predict and mitigate volcanic hazards?

Wildfires

What is the impact of global biomass burning on the terrestrial biosphere and atmosphere, and how is this impact changing over time? A LWIR sensor will allow us to measure temperature, emissivity, radiative flux, burn products, hot spots, etc.

Water Use and Availability

As global freshwater supplies become increasingly limited, how can we better characterize trends in local and regional

water use and moisture availability to help conserve this critical resource?

Urbanization

How does urbanization affect the local, regional and global environment? Can we characterize this effect to help mitigate its impact on human health and welfare?

Land surface composition and change

What is the composition and temperature of the exposed surface of the Earth? How do these factors change over time and affect land use and habitability?

The QWEST testbed is providing enabling technology for the development of a fully operational airborne platform suitable for earth science studies. It will have sufficient spatial and spectral resolution to allow scientists to acquire the necessary data to aid in the planning of future spaceborne missions.

2. OPTICAL DESIGN

Concentric designs allow a point to be mapped perfectly to a focal plane array. Past and future planned imaging spectrometer systems have successfully implemented the Offner [3,4] design. The idea behind the Offner concentric design was to provide a relay unit magnifier to alleviate distortion and third order system aberrations while having an accessible object and image plane. The first published supplementary idea for an all reflecting or 2-mirror concentric imaging spectrometer was cast by Thevenon and Mertz [5]. Subsequent work was also done by Kwo [6] and Lobb [7]. A concentric design like the Offner is well-suited to pushbroom spectrometers. Smile and keystone distortion are nearly eliminated using proper alignment and design techniques.

The Offner design would be relatively large and would require a bulky temperature controlled dewar and large power supplies to maintain adequate thermal control for the LWIR. J. Dyson [8] published a paper in 1959 outlining a Seidel-corrected unit magnifier which was composed of a single lens and concave mirror. It was to be used to project groups of lines for emulsion photography and also phase contrast microscopy. Mertz also proposed the Dyson principle in the same paper where he discussed the Offner. Wynne [9] proposed a Dyson design for microlithography in the visible and ultraviolet and Mouroulis [10,11] et al. considered Dyson designs for visible spectrometry and for coastal ocean applications. A thorough treatment of these designs as well as an operational thermal infrared system is described in work by Warren et al [12]. Kuester [13] et al. discuss an airborne platform which uses a visible transmitting Dyson.

Our effort uses the same principle but extends the Dyson design to work optimally with the LWIR. The savings in

physical size for similar low F/# systems is dramatic. QWEST was designed to minimize smile and keystone distortion [14] while simultaneously virtually eliminating ghosting. The slit width is 50 μm , which corresponds to two detector pixels. Smile and keystone distortions were kept to no more than 1-2% of this or $\sim 2\mu\text{m}$. JPL fabricates ultra precision slits using reactive ion etching which can be kept straight to an order of magnitude better than this. For this reason the slit straightness is not typically the limiting factor in spectrometer performance.

As shown in figure 1, a single monolithic block is used in double pass where light from the slit enters at a narrow optical passageway and is transmitted through the rear power surface, diffracts off the grating and re-enters the block to totally internally reflect off the back surface which guides the spectrally dispersed radiation to focus at the QWIP location. This design minimizes the travel and form factor of the system. The actual block fabricated is shown in figure 2. Broadband area coatings are used on all applicable light transmitting surfaces. The coatings allow 99.0% or better LWIR light to transmit. The block was fabricated from ZnSe, a robust material with a transparent wavelength region from 0.4 \sim 23 μm and an absorption coefficient between 10^{-3}cm^{-1} and 10^{-4}cm^{-1} . The ZnSe slab is produced by chemical vapor deposition.

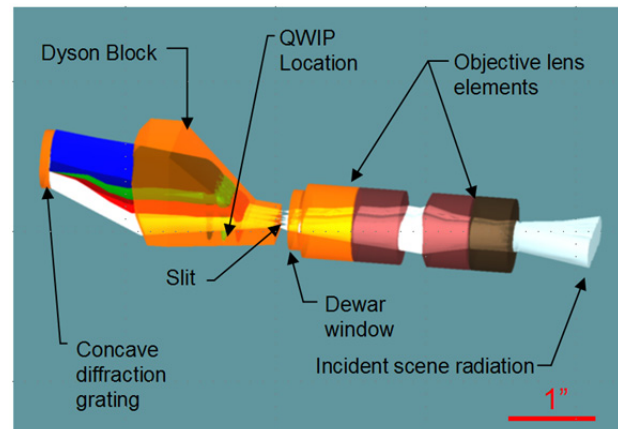


Figure 1. Conceptual layout of Dyson spectrometer and objective lens elements

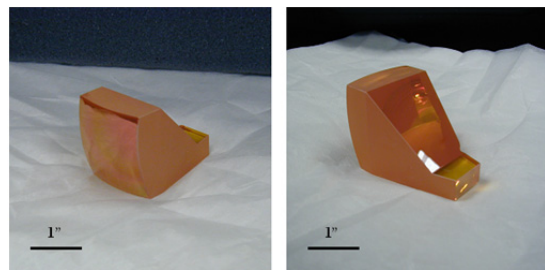


Figure 2. Monolithic ZnSe optical block with BBAR coatings used in double pass for the Dyson spectrometer

3. THE QWIP ARRAY

QWIP technology [15,16,17] utilizes the photoexcitation of electrons between the ground state and the first excited state in the conduction band quantum well (QW). QWIPs have been successfully integrated into commercial handheld field units for more than a decade. This is the first integration of the QWIP with a spectrometer system for earth science studies requiring accurately calibrated data.

The detector pixel pitch of the FPA is 25 μm and the actual pixel area is 23x23 μm . Indium bumps were evaporated on top of the detectors for hybridization with a silicon readout integrated circuit (ROIC). These QWIP FPAs were hybridized (via indium bump-bonding process) to a 640x512 pixel complementary metal-oxide semiconductor (CMOS) ROIC and biased at $V_B = -1.25$ V. At temperatures below 72 K, the signal-to-noise ratio of the system is limited by array nonuniformity, readout multiplexer (i.e., ROIC) noise, and photocurrent (photon flux) noise. At temperatures above 72 K, the temporal noise due to the dark current becomes the limitation. We are currently running the system at 40K to have a SNR advantage. The QWIP is known for its high spatial uniformity (<0.51%). This is a clear advantage over other detector technologies such as HgCdTe and InSb. A custom made LCC and titanium FPA clamp was designed to accommodate the close proximity (~mm's) of the FPA with the ZnSe block.

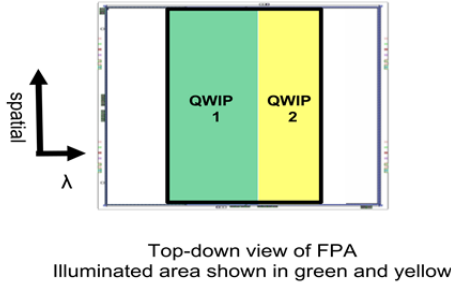


Figure 3. QWIP and custom made clamp assembly to hold QWIP and leadless chip carrier (LCC)

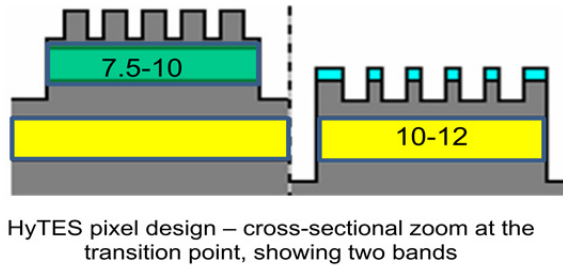


Figure 4. QWIP material structure for 2-band system.

4. DIFFRACTION GRATING

Diffraction grating design and fabrication is a key enabling technology for these spectrometers. JPL has developed electron-beam lithography techniques that allow fabrication of precisely blazed gratings on curved substrates having several millimeters of height variation [18,19,20]. Gratings fabricated in this manner provide high efficiency combined with low scatter. The blazed grating for this LWIR Dyson spectrometer was fabricated in a thin layer of PMMA electron-beam resist coated on a diamond-turned concave ZnSe substrate. After exposure and development to the desired blaze angle, the resist was overcoated with gold for maximum infrared reflectance. A photograph of the grating and the simulated efficiency of the fabricated grating are shown in figures 5a and 5b, respectively. The design was optimized for maximum efficiency in the -1 order, and the other orders remain relatively weak across the band.

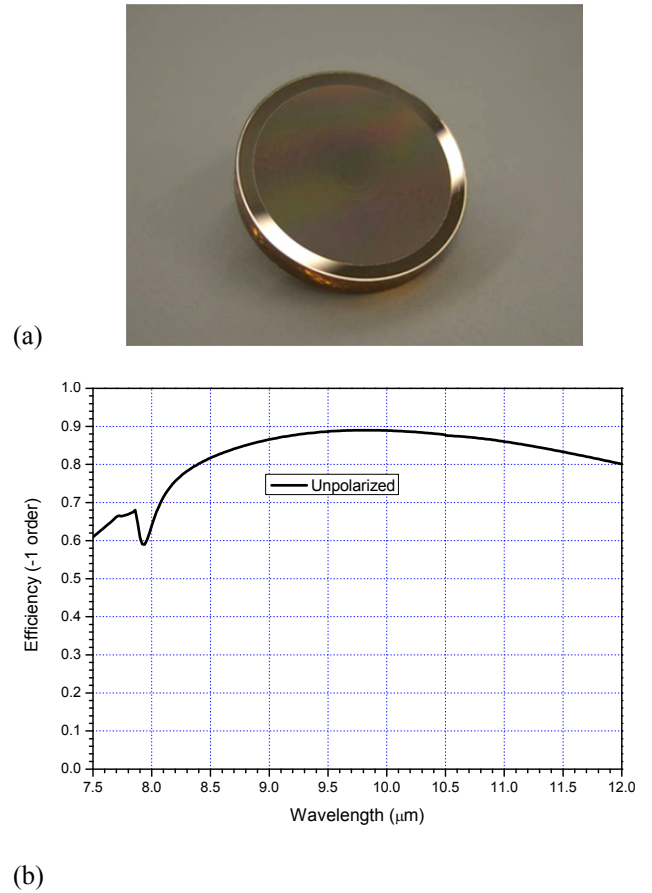


Figure 5. QWEST spectrometer grating: (a) photograph of fabricated grating (annular E-beam focus zones are visible due to slight variation in scattering; unexposed rectangular areas near edge are due to the E-beam mount), (b) simulated efficiency (calculated using PCGrate 6.1 software).

5. SYSTEM SPECIFICATIONS AND RESULTS

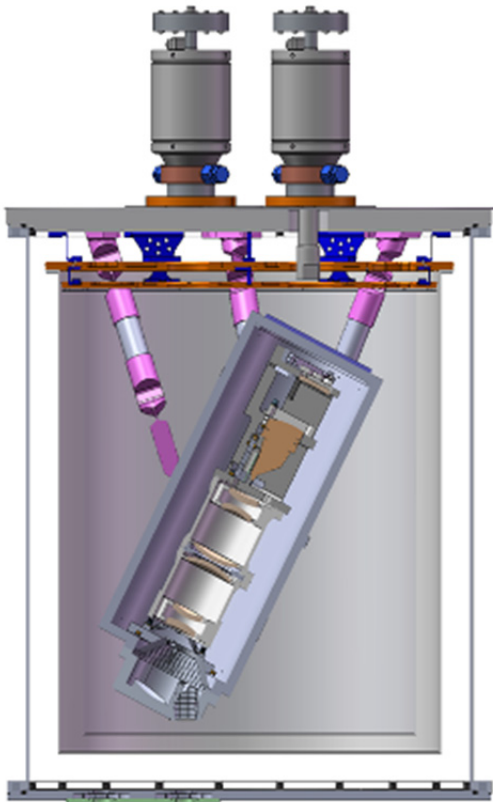
The main goal of this effort was to show as a proof of concept that high quality data can be obtained using the combination of Dyson spectrometer with QWIP detector. Total system isolation from stray light past the spectrometer slit was established by cryogenically cooling all opto-mechanical structures to 40K. This is reasonable due to the small form factor of the system. Currently, stray light analysis using FRED (Photon Engineering, LLC) is being performed to assess further direction in design for HyTES.

The basic specifications of QWEST and HyTES are shown in figure 6a with a system layout of the instrument in figure 6b. Both systems will use large format detectors and have large spatial swath widths. The current optical design and grating works for the entire 7.5 - 12 μ m regime but the existing QWIP FPA which is being used for preliminary testing in QWEST is only sensitive from 7.5-9.5 μ m (nearly equivalent to band 1 as shown in figure 3). The broadband QWIP installation is currently underway and results will be presented in future publications. The close proximity of all electro-optical components can be appreciated in figure 7. This shows the ZnSe block and hardware in nearly its final configuration.

Instrument Characteristic	QWEST	HyTES
Number of pixels x track	320	512
Number of bands	256	256
Spectral Range	8-12 μ m	7.5-12 μ m
Integration time (1 scanline)	30 ms	30 ms
Total Field of View	40 degrees	50 degrees
Calibration (preflight)	Full aperture blackbody	Full aperture blackbody
QWIP Array Size	640x512	1024x512
QWIP Pitch *	25 μ m	19.5
QWIP Temperature	40K	40K
Spectrometer (Dyson) temperature	40K	40K
Slit Width	50 μ m	39 μ m
Pixel size at 2000 m flight altitude	4.5 m	3.64
Pixel size at 20,000 m flight altitude	45 m	36.4

a)

Figure 6. a) schematic concept of Dyson spectrometer and b) Final system specifications for QWEST and expected for HyTES



b)

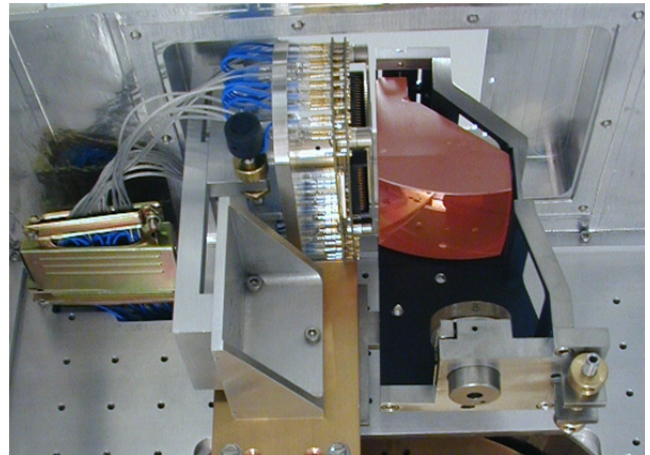


Figure 7. Dyson spectrometer tested in dewar environment.

HyTES predicted NEDT is shown in figure 8. A spectral calibration was performed using narrowband interference filters. This is an easy way to determine the position of the spectral bands and verify the full width at half maximum. For radiometric performance, a National Institute of Standards and Technology (NIST) traceable transfer calibration is performed on our electro-optic blackbody to verify its performance between the two end bracket temperatures of 4C and 40C. JPL has multiple NIST traceable blackbodies with a stability at 25 C of ± 0.0007 C and a thermistor standard probe with an accuracy of 0.0015 $^{\circ}$ C over $0-60$ $^{\circ}$ C and stability/yr of 0.005. A transfer calibration of the NIST traceable blackbody with the one used for the tests was performed in a ramp and soak mode where the blackbody temperature is increased by a set interval and allowed to soak for several minutes and then the temperature is measured. We use a 2-point non-

uniformity correction [21,22,23] where 4C and 40C are used to bracket the temperature range. The blackbody is ramped from 4C to 400C and then is left to drift in 5C increments to finally end up back at 4C. Frames are taken at each interval to check for both temporal artifacts as well as single frame noise equivalent temperature difference per spectral band as well as determining any spectral non-linearity.

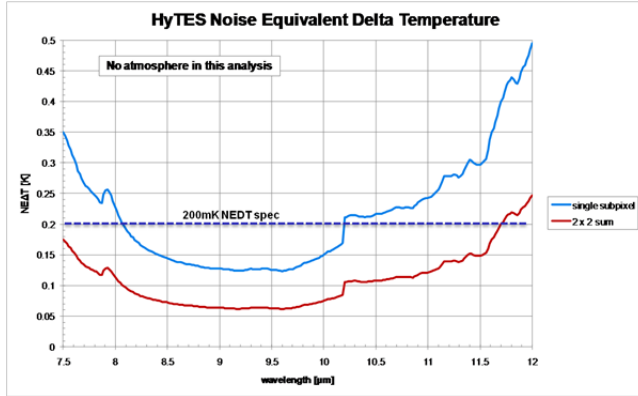


Figure 8. Predicted NEDT for single pixel and 2x2 binned effective pixel. The performance meets expectation.

Two tests were performed to characterize the instrument performance. Test one was for spectral linearity while the other determined the spectral NEDT. The data shows that QWEST has very good linearity with many temperature measurements showing absolute errors below 0.1C. The noise equivalent delta temperature for spectral channels at blackbody temperatures between 5C and 30C is measured as predicted. This implies that for a given temperature between this range QWEST has a mean NEDT of 124.7mK.

The current system is being operated outdoors under direct sunlight to understand and characterize the science usefulness of the instrument towards remote sensing earth science applications. The data shown is using an integration time of 30ms and observed at roughly noon time (Pacific Standard Time). Figure 9 shows radiance calculated for a gold standard. This plot shows atmospheric water band absorption and appears to be both spectrally and radiometrically accurate when compared output from MODTRAN and previously deployed Fourier transform imaging spectrometers (FTIR), respectively.

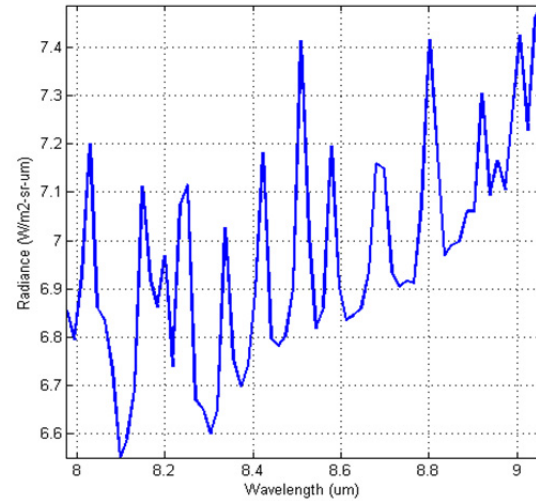


Figure 9. Radiance of gold standard with superimposed atmospheric bands as measured in direct sunlight.

This data is then used in part to further reduce data taken with the system in direct sunlight. As shown in figure 10, Quartz deposits within Ottawa sand are found with the following apparent emissivity. This compares favorably with previously taken data [24].

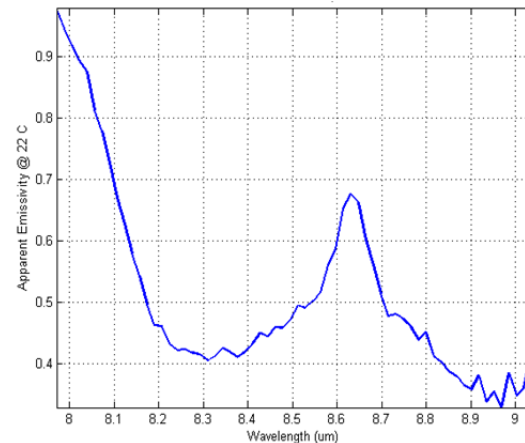


Figure 10. Apparent emissivity of quartz as measured by QWEST in direct sunlight.

6. REMARKS

A small form factor long wave infrared Dyson spectrometer using a QWIP focal plane array has been demonstrated. The main advantage of the QWIP technology is its excellent spatial uniformity (< 0.5%) variability. Preliminary results show measured NEDT and linearity are excellent. The same spectrometer performance over the nominal LWIR bandpass (8-12μm) is expected once the broadband QWIP installation is completed. Future effort will start to optimize the system using alignment techniques (both cold in rotation and using temperature cycles) to achieve required smile and keystone

performance, install the broadband 8-12 μm QWIP focal plane array, perform field work to support the earth science testbed effort and begin the transition to a cryocooler airborne instrument.

Super lattice detectors [25] which are also being fabricated at JPL have the potential of offering similar uniformity but with a higher operating temperature and higher QE. Future Dyson platforms may be able to take advantage of this technology as well.

7. ACKNOWLEDGEMENTS

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BIOGRAPHY



William R. Johnson is an Optical Engineer and Technologist at the Jet Propulsion Laboratory. He completed his M.S. degree at the University of Arizona and has been employed at JPL ever since. He works on advance imaging spectrometer devices and data reduction techniques with a specific interest in the generalized problem of quantitative spatial and spectral modulation.



Simon J. Hook received his B.Sc. in 1982 from the University of Durham, England, M.Sc. in 1985 from the University of Edmonton, Canada, and PhD., in 1989 from the University of Durham, England all degrees were in geology. He is a principal scientist at the Jet Propulsion Laboratory JPL. His research is focused on improving our understanding of geologic and hydrodynamic processes on Earth and other planets.



Pantazis Mouroulis is a graduate of the University of Athens _BSc in physics 1976 and the University of Reading MSc and PhD in optics 1981. He is at present a senior research scientist and principal engineer at the Jet Propulsion Laboratory JPL, where he supervises an optical technology group. His recent research interests focus on instrumentation for imaging spectroscopy.



Dr. Daniel W. Wilson received the PhD in electrical engineering from the Georgia Institute of Technology in 1994. He is currently a principal engineer in the Microdevices Laboratory at Jet Propulsion Laboratory, California Institute of Technology. His research interests include the design, modeling, and electron-beam fabrication of diffractive optical components and instruments. Since joining JPL, he has contributed to the successful development of high performance convex diffraction gratings, coronagraph occulting masks, transient-event imaging spectrometers, and particle velocity sensors.



Dr. Sarath D. Gunapala received his PhD in physics from the University of Pittsburgh in 1986. Since then he studied infrared properties of III-V compound semiconductor hetero-structures and the development of quantum well infrared photodetectors (QWIPs) for infrared imaging at AT&T Bell Laboratories. He joined NASA's Jet Propulsion Laboratory at California Institute of Technology in 1992. There, he leads the Infrared

Focal Planes & Photonics Technology Research Group. Also, he is a senior research scientist and a principal member of the engineering staff at NASA Jet Propulsion Laboratory. Dr. Gunapala has authored over 250 publications, including several book chapters on infrared imaging focal plane arrays, and holds seventeen patents. He is a SPIE Fellow and Senior Member of IEEE.

Jason Mumolo received his B.S. degree in electrical engineering from polytechnic University of California, Pomona in 2001. He joined the Jet propulsion Laboratory, California Institute of technology in Pasadena in 1997 as an undergraduate part-time student. He's current work and interest is in developing and fabrication of QWIP devices and other advance focal plane arrays for camera systems.

